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# Development of a Water Pipe Monitoring System for Leak Detection: Experimental Work

**J.M. Muggleton, M.J. Brennan and R.J. Pinnington**

ISVR Technical Memorandum 860

January 2001

University of Southampton

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INSTITUTE OF SOUND AND VIBRATION RESEARCH

DYNAMICS GROUP

# Development of a Water Pipe Monitoring System for Leak Detection: Experimental Work

by

**J.M. Muggleton, M.J. Brennan and R.J. Pinnington**

ISVR Technical Memorandum No. 860

January 2001

Authorized for issue by
Dr. M.J. Brennan
Group Chairman

## Abstract

In this report, experimental work carried out under EPSRC research project GR/M39428, 'Development of a water pipe monitoring system for leak detection' is described. The work had two distinct strands, as set out in the project proposal. The first was to investigate the use of a piezoelectric wire transducer in measuring sound pressure inside a buried pipe, and the integration of this transducer with existing leak noise correlation equipment; the second concerns the validation of an analytical model predicting the axisymmetric wavespeed and attenuation in a buried fluid-filled pipe.

Two types of PVDF (polyvinylidene fluoride) wire have been calibrated as ring transducers for measurement of the pressure inside an elastic, fluid-filled pipe; furthermore, preliminary tests have been undertaken on two novel, part-ring transducers. The complete ring transducers have been integrated with existing leak noise correlation equipment, and a simulated leak has been detected.

Measurements of Young's modulus and loss factor have been made on a number plastic samples, typically used in the water industry, as a pre-requisite for predicting wave behaviour in plastic water pipes. A procedure for making wavenumber measurements of the 'fluid-borne' axisymmetric wave in a pipe has been developed, and measurements have been made on a polyethylene pipe in the laboratory. These measurements show good agreement with predictions from the analytical model.

Finally, a brief description of a buried pipe facility at the University of East Anglia, Norwich, is included, on which measurements will be made in the near future.

# Contents

# 1. *Introduction*

In this report, experimental work carried out under EPSRC research project GR/M39428, 'Development of a water pipe monitoring system for leak detection', is described. The work has two distinct strands, as set out in the project proposal. The first is to investigate the use of a PVDF (polyvinylidene fluoride) piezoelectric wire transducer in measuring sound pressure inside a buried pipe, and the integration of this transducer with existing leak noise correlation equipment; the second concerns the validation of an analytical model predicting the axisymmetric wavespeed and attenuation in a buried fluid-filled pipe. The wire transducer was devised and preliminary tests were undertaken in the laboratory as part of an earlier project [1,2]. Some of the measurements have been repeated here for the sake of completeness.

Section 2 of this report describes the theoretical basis for the wire as a pressure transducer, and calibration measurements are described. In addition to the previously used type of wire being calibrated, a new type of wire, recently developed by the manufacturer, has also been calibrated and assessed for its suitability as a pressure transducer.

Section 3 describes initial experiments on two variants of a modified form of the ring transducer, for use where the whole of the pipe circumference is not accessible, as is often the case in real water pipe networks.

Section 4 describes preliminary experiments in the field with complete ring sensors, integrating the sensors with current leak detection equipment.

In order to make reliable predictions about the wave propagation in any plastic water pipe, the elastic properties of the pipe wall must be known in advance. Section 5 describes the measurement of the Young's modulus and estimation of the structural loss factor of plastics typically used in the water industry.

Section 6 describes the measurement of the wavenumber of the axisymmetric 'fluid-borne' wave in a plastic pipe in the laboratory. This procedure will serve as the basis for future wavenumber measurements made both in the laboratory and in the field.

Finally, the collaboration with the University of East Anglia, Norwich (UEA) is described. A research team at UEA, Norwich have a buried pipe facility on campus at UEA. The ISVR team have collaborated with UEA, and have installed sensors on their rig, with a view to making measurements in the future.

## 2. *Calibration of PVDF ring sensors to measure internal pressure in a pipe*

### 2.1 *Introduction*

Two types of PVDF wire were calibrated for measuring the axisymmetric 'fluid-borne' wave in a fluid-filled pipe. The first was Vibetek 20 wire, which has previously been used as a ring transducer [1,2]; Unfortunately, however, Vibetek 20 is discontinued at present, due to concerns over toxicity of some of its constituents. A new type of wire, Vibetek OT017 is currently being developed which does not suffer from the same drawback, but unfortunately is much less sensitive to longitudinal elongation. This wire, still in the developmental stages was provided by the manufacturers for evaluation. Measurements were made on a perspex pipe and compared with theoretical predictions based on wire data supplied by the manufacturers and the theoretical modelling described in [1]-[3].

### 2.2 *Theoretical basis*

Data on the PVDF wires supplied by the manufacturer, Ormal Ltd, was in the form of piezoelectric charge coefficient, $e_{31}$, and the diameters of the core and whole wire, $X$ and $Y$ respectively.

| Wire type | $e_{31}$ (pC/m$^2$) | Y (m) | X (m) | Charge/extn (pC/m) |
|---|---|---|---|---|
| Vibetek 20 | $8.0 \times 10^{10}$ | $1.45 \times 10^{-3}$ | $0.45 \times 10^{-3}$ | $2.15 \times 10^{8}$ |
| Vibetek OT017 | $9.0 \times 10^{9}$ | $1.40 \times 10^{-3}$ | $0.65 \times 10^{-3}$ | $2.76 \times 10^{7}$ |

Table 2.1

PVDF wire constants as supplied by Ormal Ltd [4]

The piezoelectric charge coefficient is related to the charge generated by the wire, $Q$, the longitudinal strain, $\Delta L/L$, and the effective electrode area, $A$, by [4]

$$e_{31} = \frac{Q}{\Delta L / L}\frac{1}{A} \tag{2.1}$$

where

$$A = \frac{\pi L(Y - X)}{\ln\left(\frac{Y}{X}\right)} \tag{2.2}$$

The charge per unit extension of the wire, $Q/\Delta L$, is therefore given by

$$\frac{Q}{\Delta L} = e_{31}\pi\frac{(Y-X)}{\ln\left(\frac{Y}{X}\right)} \tag{2.3}$$

This formulation is an agreement with that given previously by Rex [5]. Table 2.1 shows the wire constants along with the charge sensitivity per unit extension for each of the wire types, revealing that the Vibetek OT017 wire will be much less sensitive as a pressure transducer than the Vibetek 20 wire.

Reference [3] showed that, at low frequencies, where there is less than one half of a fluid wavelength across the pipe diameter, for the axisymmetric 'fluid-borne' wave in a fluid-filled pipe, the magnitude of the radial extension of the pipe wall, $W$, is related to the magnitude of the internal pressure in the fluid, $P$, via

$$P = -\frac{2\omega^2 \rho_f}{\left(k_f^r\right)^2 a} W \tag{2.4}$$

where, $\rho_f$ is the fluid density, $a$ is the mean pipe radius, and $k_f^r$ is the radial fluid wavenumber, related to the fluid wavenumber, $k_f$, and axial wavenumber, $k$, by

$$\left(k_f^r\right)^2 = k_f^2 - k^2 \tag{2.5}$$

Reference [3] also showed that, at low frequencies, in the absence of a surrounding medium, the axial wavenumber, $k$, is related to the fluid wavenumber, $k_f$, by

$$k^2 = k_f^2\left(1 + \frac{2B_f a}{Eh}\right) \tag{2.6}$$

where $B_f$ is the bulk modulus of the contained fluid, $E$ is the elastic modulus of the pipe wall, and $h$ is the pipe wall thickness.

Substituting equations (2.5) and (2.6) into equation (2.4), and rearranging gives

$$P = \frac{Eh}{a^2} W \tag{2.7}$$

This is the static relationship between internal pressure and radial displacement for a ring [6].

If a wire is wrapped N times around the pipe circumference, the extension of the wire, $w_{ext}$, is related to the mean radial displacement of the pipe wall, $W$, by

$$w_{ext} = 2\pi N \frac{a_{max}}{a} W \tag{2.8}$$

where $a_{max}$ is the outer pipe wall radius.

Furthermore, if $S$ is the charge sensitivity of the wire per unit extension, the pressure sensitivity of the wire $S_p$ (charge per unit pressure within the pipe) is, from equations (2.7) and (2.8) given by

$$S_p = \frac{2\pi Naa_{\max}}{Eh} S \tag{2.9}$$

## 2.3 *Experimental set-up & procedure*

The experimental arrangement is shown in figures 2.1-2.3. It consisted of a water-filled perspex pipe, approximately 2m in length, secured vertically, with the lower end sealed. The water column was excited at the upper end by an electrodynamic shaker attached to a light, rigid piston. The external diameter of the pipe was 150mm, with the wall thickness being 6mm. The pipe was instrumented with a Vibetek 20 PVDF wire transducer in the centre section of the pipe, and a B&K 8103 hydrophone was hung vertically to measure the internal pressure at the same height, as determined by visual inspection. The piston was excited with a swept sine input from 5Hz to 1kHz, and the signals from the PVDF wire transducer and the hydrophone were acquired into an HP analyser. Using the supplied pressure sensitivity for the hydrophone, and that calculated for the wire using equation (2.9) above, the pressure responses were compared by inspecting the ratio of the two measurements. The hydrophone position was then slightly adjusted and the measurements repeated until it was considered that the acoustic centres of the two transducers were as well aligned vertically as possible. The measurements were then repeated, comparing Vibetek OT017 wire with a hydrophone.

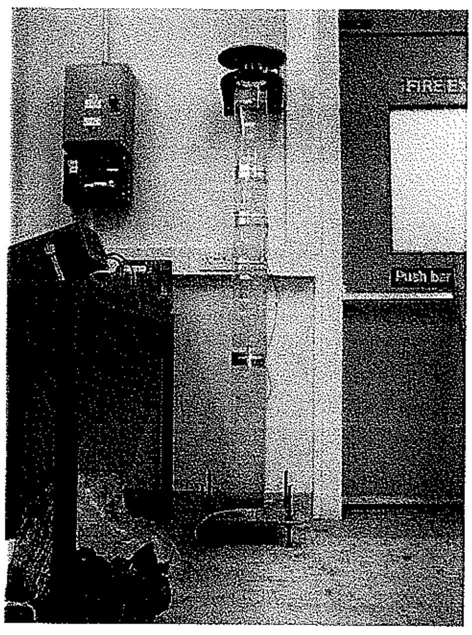



Figure 2.1

Perspex pipe

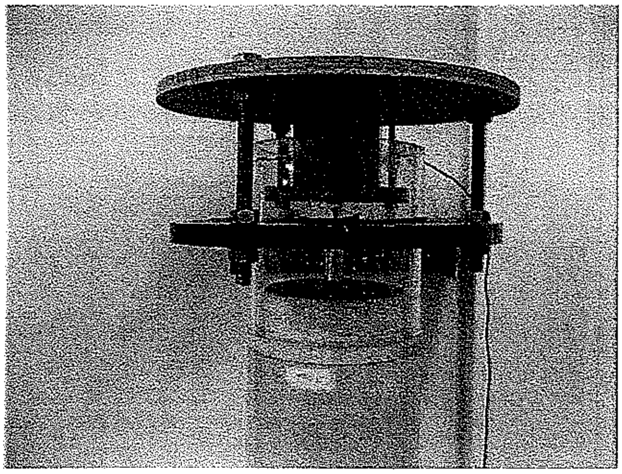


Figure 2.2

Piston arrangement

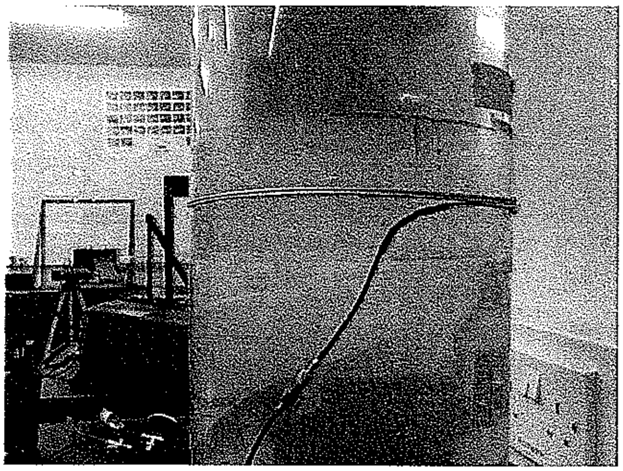
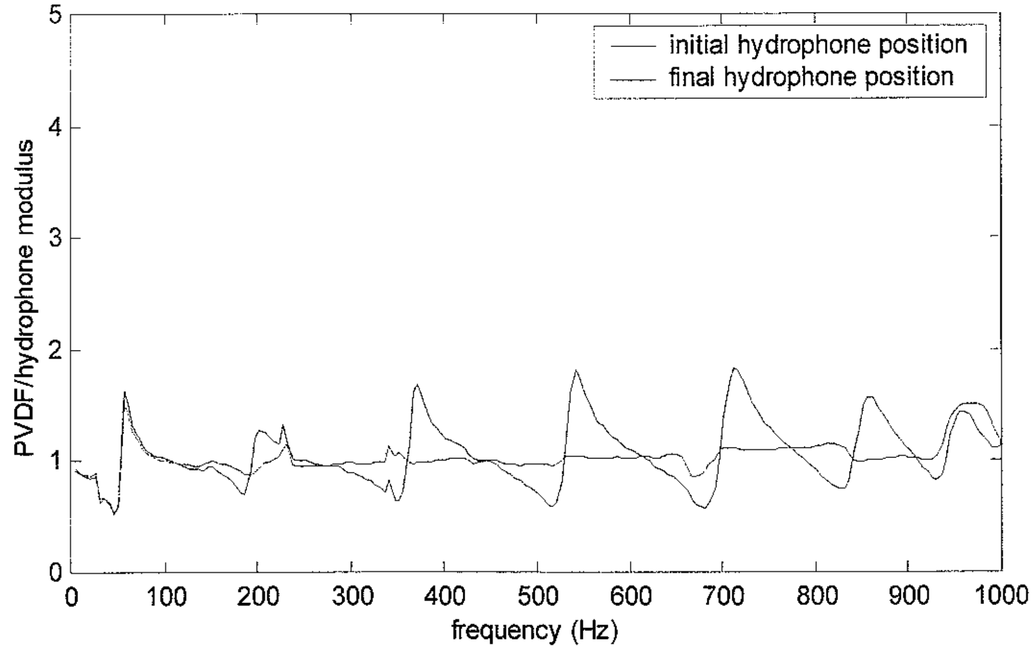


Figure 2.3

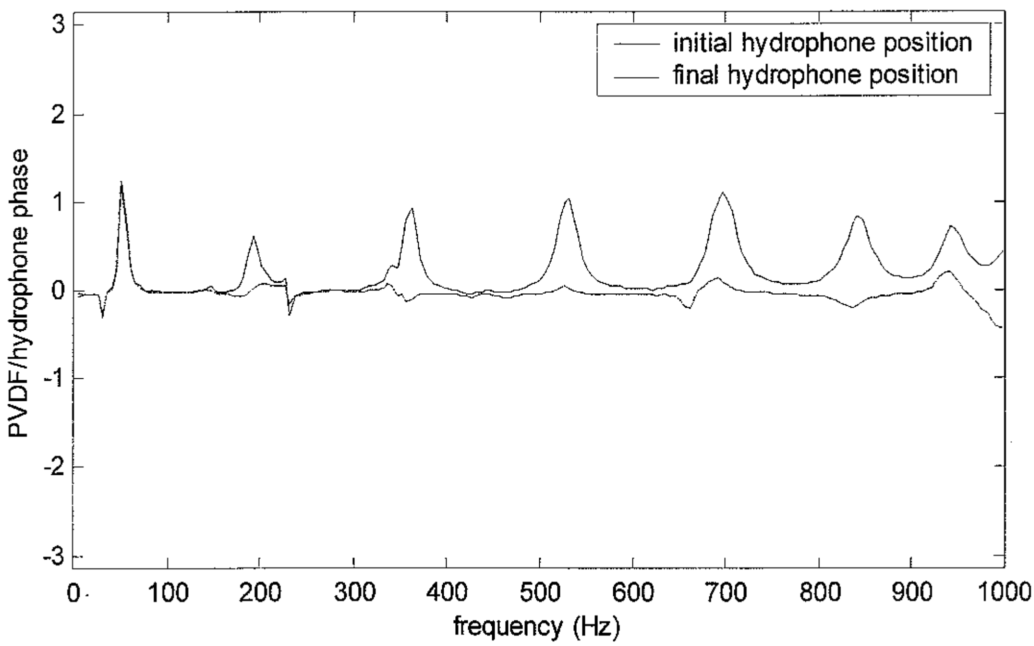
PVDF wire

## *2.4 Results & discussion*

Figure 2.4 show the modulus and phase of the pressure measured by the Vibetek 20 wire, relative to that measured by the hydrophone inside the pipe. It can be seen that, with the hydrophone in its final position, the response is fairly flat, and equal to one as expected, showing that the hydrophone and the wire are both measuring the same pressure. There is a slight peak at 50Hz, associated with the mains supply. Inspection of the curves for with the hydrophone in its initial position shows the effect of a slight misalignment of the two transducers. The peaks in the response correspond to pressure minima as measured by the wire, when the ratio between the two signals will be the largest if the transducers are not aligned correctly. The residual peaks in the graphs with the hydrophone in its final position suggest that there is still a slight misalignment present, despite efforts to minimize it.




(a)

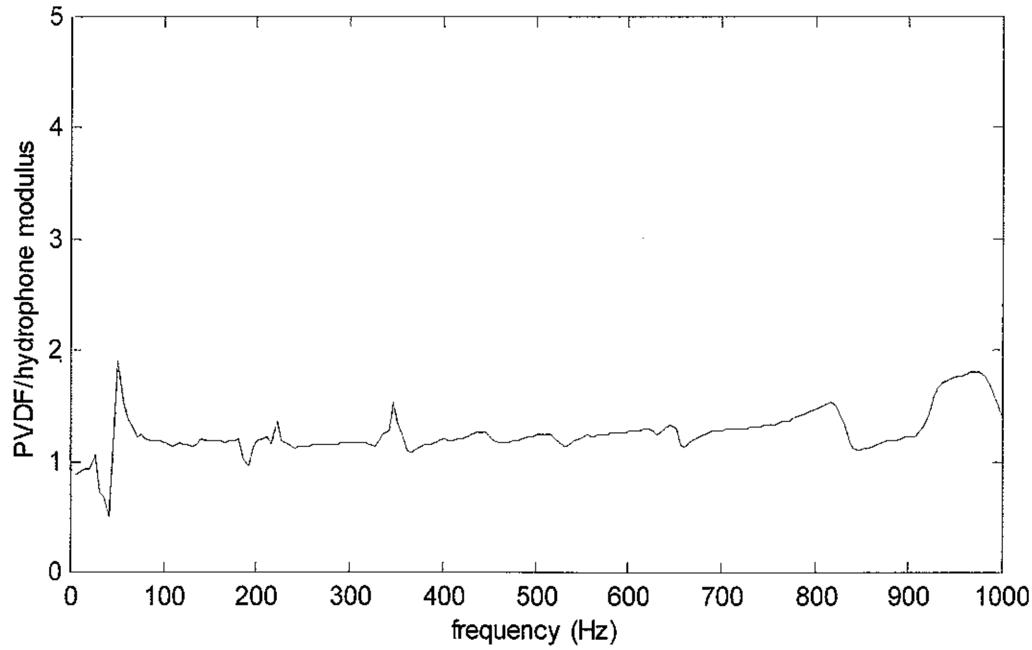



(b)

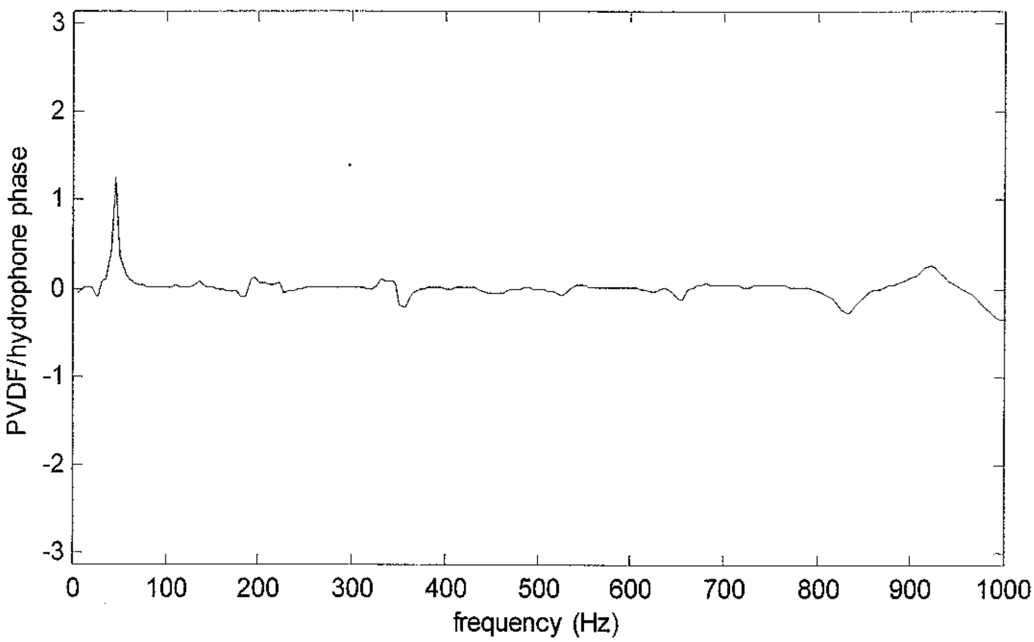
Figure 2.4

(a) Modulus & (b) phase of wire response relative to hydrophone response

Vibetek 20 wire




(a)




(b)

Figure 2.5

(a) Modulus & (b) phase of wire response relative to hydrophone response

Vibetek OT017 wire

Figure 2.5 shows the corresponding plots for the Vibetek OT017 wire, with the hydrophone in its final position only. Again, the deviations from a completely flat response suggest a minor misalignment. However, in this case, although the signals from the two transducers are in phase, the pressure measured by the wire is slightly higher than expected (by about 20%), suggesting that the wire is slightly more sensitive than predicted. Given that the wire is still in the developmental stage, this anomaly has not been pursued further for the present, as it may be that the wire constants provided by the manufacturer were not accurate.

## *2.5 Summary*

Both the Vibetek 20 and the Vibetek OT017 wires can be used as ring transducers to measure pressure in side a flexible water-filled pipe, having a flat response at frequencies well below the ring frequency of the pipe. For the Vibetek 20 wire, the pressure sensitivity can be accurately predicted from the wire constants and the pipe properties. The pressure sensitivity for the Vibetek OT017 wire is much lower (about 15% of the Vibetek 20 value), but appears to be slightly higher than predicted from the wire constants supplied with the wire. Further data on this wire is required before more definitive statements can be made.

# 3 *Testing of part-ring transducers*

## 3.1 *Introduction*

One of the disadvantages to the PVDF ring transducer in its usual configuration of an integer number of turns around a pipe is that the complete circumference of the pipe must be accessible in order to instrument the pipe. In many real pipework installations, the lower portion of the pipe is buried, and only a small percentage of the circumference can be reached. With this in mind two configurations of wire which only required access to a short length around the pipe were tested in the laboratory.

## 3.2 *Experimental set-up & procedure*

The configurations are shown in figures 3.1 and 3.2. The first consisted of wire wrapped back and forth over a short section whilst attempting to achieve as tight a curve as possible at the ends without damaging the wire (zig zag configuration); the second consisted of a number of separate wires connected together such that the signals from the wires were summed. These configurations were calibrated on a perspex pipe against a hydrophone using the method described in section 2, and the results compared with those obtained using the fully wrapped configuration. The pressure sensitivities of the wires were calculated by assuming that they would be equal to the sensitivity of a complete loop transducer of the same overall wire length.

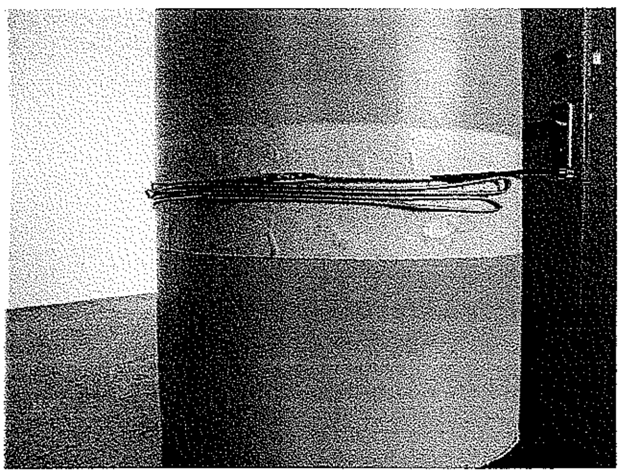


Figure 3.1
Zig zag wire configuration

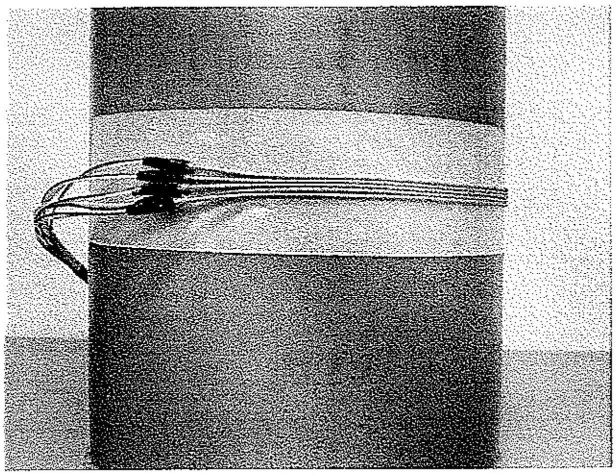
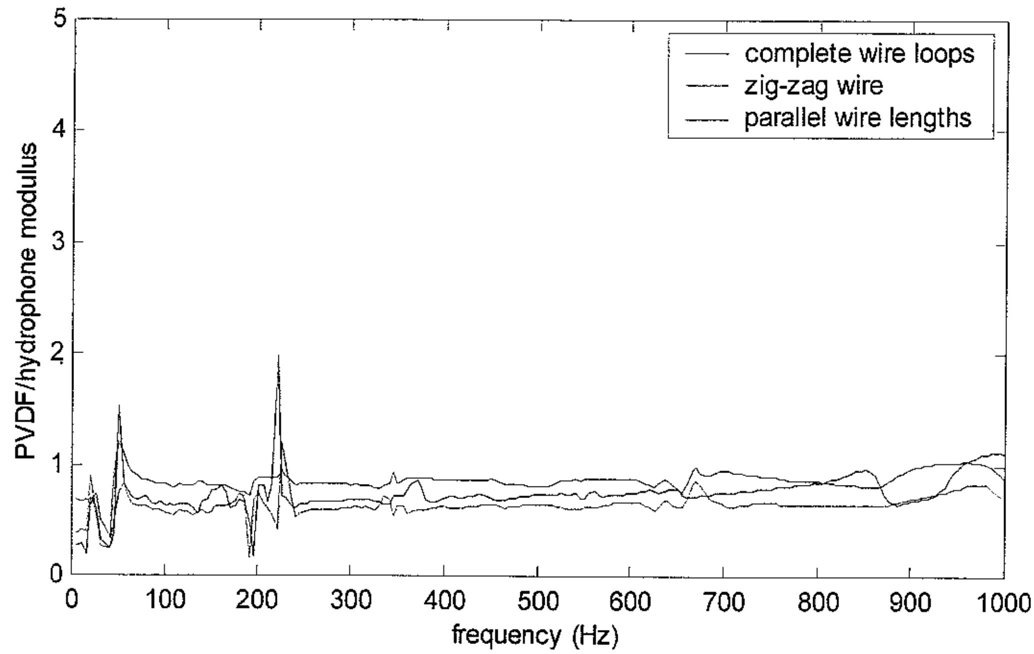


Figure 3.2
Parallel wire configuration

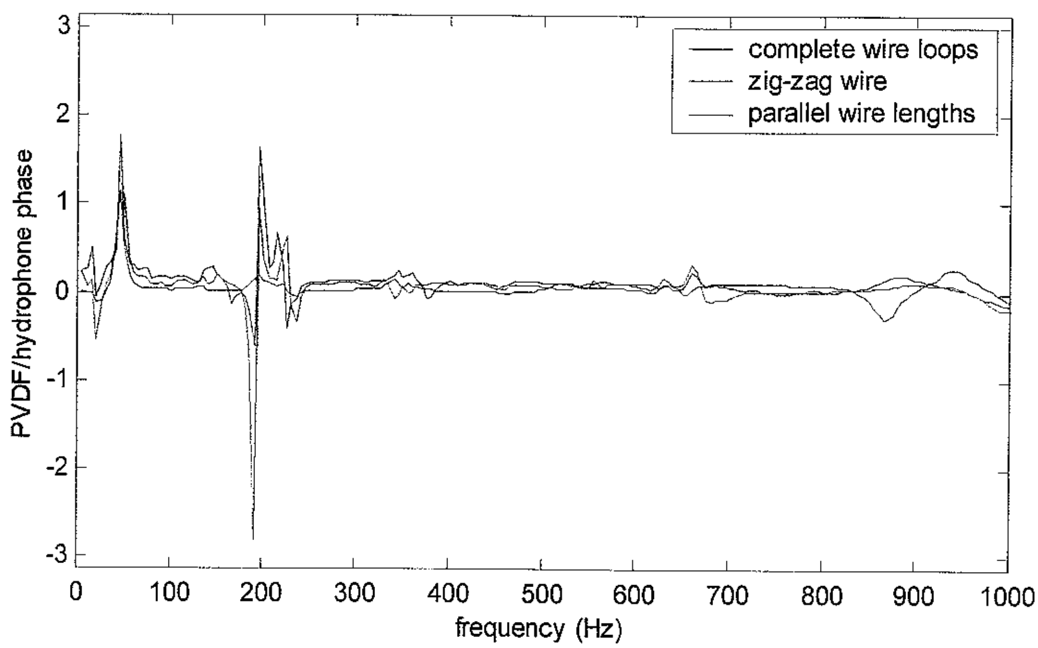
## *3.3 Results & discussion*

Figure 3.3 shows the modulus and phase of the wire response relative to the hydrophone response for three different wire configurations: complete wire rings; zig zag loops (figure 3.1); and parallel wire lengths (figure 3.2). With the exception of the peaks around 50Hz (probably due to mains), and around 200Hz (for the zig zag and parallel wire configurations), the wire responses are largely flat over the frequency range considered. The relative phase for all three wire transducers, compared with the hydrophone, is zero, as anticipated. The magnitude of the responses for the zig zag and parallel wire configurations is lower than for the complete loop case, with the zig zag configuration being the lower of the two. For both of these wires, end effects are likely to be the cause: for the zig zag wire, the non zero curvature at the end turns means that not all the wire runs around the pipe as is required; for the parallel wire configuration, the presence of the connectors at the wire ends tends to splay the wires out (see figure 3.2), so again, not all of the wire is in the appropriate alignment. Furthermore, for the zig zag wire, it was found that bending the wire at the ends into too tight a curve resulted in damage to the outer coating of the wire, and potential degradation of its performance; this problem did no occur for the parallel wire configuration.

One of the advantages of the wire transducer in its original configuration of complete rings is that it is most sensitive to axisymmetric motion of the pipe wall, and relatively insensitive to higher order modes of the pipe. Thus the pressure measured will largely be associated with the n=0 axisymmetric modes. This is not so for the two new configurations of wire tested here, and this may be the cause of the peaks in the responses seen at around 200Hz. Further tests would need to be undertaken in order to establish this.




(a)




(b)

Figure 3.3

(a) Modulus & (b) phase of wire response relative to hydrophone response

## *3.4 Summary*

Both new configurations tested in general measure internal fluid pressure as expected, but give slightly reduced pressure sensitivity compared with a complete ring sensor of equal total wire length. The parallel wire configuration performed better than the zig zag configuration, and was found to be more robust. Problems may occur due to the sensor picking up non-axisymmetric modes. Further work is needed to establish this.

# 4. *On site measurements*

## *4.1 Introduction*

Part of the remit of this project was to integrate the PVDF ring sensor with current leak noise correlation equipment. With this in mind, in consultation with Primayer Ltd (manufacturer of leak detection equipment) and Southern Water, a site near Fareham, Hampshire, was identified at which measurements could be made.

## *4.2 Experimental set-up & procedure*

The measurement site consisted of an approximately 250m length of medium density polyethylene (MDPE) water pipe situated within a live water main network on a new housing estate. Southern water provided an access point at each end of the designated length, at which the whole circumference of the pipe could be reached. A fire hydrant was positioned between the two access points, approximately 150m from one, which could be turned on to simulate leak noise, as shown in figure 4.1.

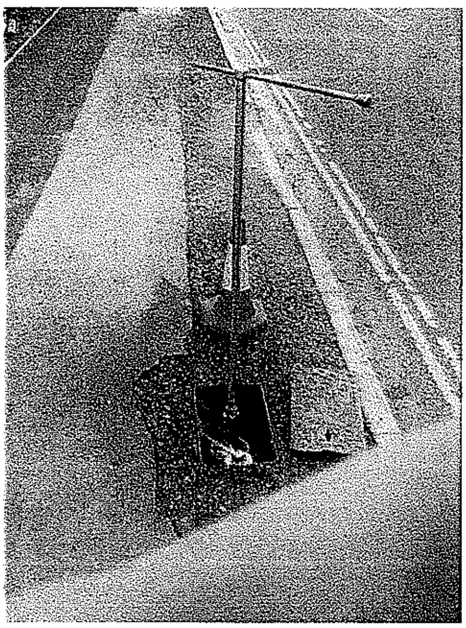


Figure 4.1
Fire hydrant simulating water leak

At each access point (figure 4.2), Vibetek 20 wire was wrapped around the pipe an integer number of times. From the estimated properties and dimensions of the pipe and the known wire constants, the pressure sensitivity of the wire was determined. The wires were connected to charge amps as in the laboratory, the outputs of which could be connected directly to the radio transmitters forming part of Primayer's leak noise correlation system (figure 4.3).

Data was acquired into the Primayer leak noise correlator first with the fire hydrant closed, and then with it open. The intention was to see if the Primayer system, using the signals from the wires, could detect the 'leak noise' from the fire hydrant.

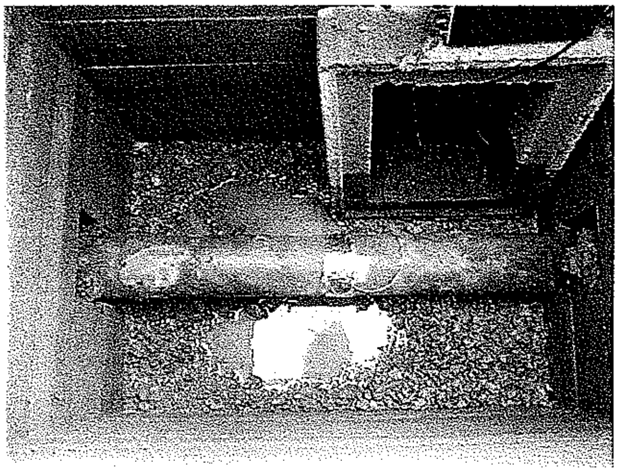


Figure 4.2

Access point with pipe instrumented with PVDF wire

Figure 4.3

Instrumented pipe showing connection to Primayer radio transmitter

## 4.3 Results & discussion

As anticipated, with the fire hydrant closed, no correlation was achieved. When the hydrant was turned on, a correlation peak was shortly seen on the display, as shown in figure 4.4. (It should be noted that collaborators at Primayer felt that a correlation would not have been achieved at all using conventional hydrophones or accelerometers; unfortunately no comparison with hydrophones was possible for this particular test.) The time delay between the arrival times of the leak noise arriving at the two sensors was found by the correlator to be 0.118s. Knowing the distances between the transducers and the fire hydrant, an average sound speed over the frequency range considered (the data was acquired at frequencies up to 3kHz) was calculated. The sound speed was found to be approximately 420m/s. This value is a little higher than might be expected; however, unfortunately there is, at present, some uncertainty regarding the wall thickness of the pipe. Furthermore, it has not yet been possible to repeat this result when the measurements have been repeated. This problem of sometimes being able to detect a leak and sometimes not, when the conditions appear to be the same is a well recognised problem within the leak detection community, and further tests are planned in the forthcoming project.

Figure 4.4

Leak noise correlator showing correlation peak

## 4.4 Summary

The PVDF ring transducer has been successfully integrated with existing leak noise correlation equipment. using a fire hydrant as a simulated leak the system achieved a correlation. The sound speed calculated was a little higher than anticipated, but no full comparison between measured and predicted data was undertaken, for lack of input data on, for example, the pipe itself. The results were not found to be easily repeatable; however, this is a common experience within the leak detection community.

# 5 Measurement of the mechanical properties of typical plastics

## 5.1 Introduction

Due to the variable nature of plastics and the lack of data on their mechanical properties, the relevant properties of a number of water pipe samples, typical of those used in the water distribution network, were measured. Density, elastic modulus and material loss factor were measured on samples of PVC (polyvinylchloride) and MDPE (medium density polyethylene).

## 5.2 Experimental set-up & procedure

Point accelerance measurements were made on short ring sections for each sample. Each ring was freely suspended, and a force was applied with an instrumented hammer in line with an accelerometer aligned radially.

The accelerance contains resonance frequencies which, for a ring, can be described by [7]

$$f_n = \frac{1}{2\pi\overline{a}}\sqrt{\frac{E}{\rho}\frac{h}{\sqrt{12}\overline{a}}\frac{n\left(n^2-1\right)}{\sqrt{n^2+1}}} \qquad (5.1)$$

where $\overline{a}$ is the mean pipe radius, $h$ is the wall thickness, $E$ and $\rho$ are the material elastic modulus and density respectively, and $n$=2,3,4... is the number of wavelengths around the ring. The elastic modulus of each sample was calculated from the frequencies of the first few resonant peaks by substitution into the above equation.

The modal loss factor of each mode, $\eta_n$, is related to the half power bandwidth of each resonant peak by

$$\eta_n = \frac{f_{n+\frac{1}{2}} - f_{n-\frac{1}{2}}}{f_n} \qquad (5.2)$$

where $f_{n+\frac{1}{2}}$ and $f_{n-\frac{1}{2}}$ are the two half power frequencies. Assuming that the modal loss factor for low order modes is of the same order as the structural loss factor, the structural loss factor at low frequencies can be found.

## 5.3 *Results*

Table 5.1 shows a summary of the results for the PVC and MDPE samples tested.

| Material | Density ($kg/m^3$) | Young's Modulus ($GN/m^2$) | loss factor |
|---|---|---|---|
| PVC | 1500-2000 | 4-5 | 0.06-0.07 |
| MDPE | 900-1000 | 1-1.5 | 0.05-0.07 |

Table 5.1

Material properties of PVC & MDPE samples

## 5.4 *Summary*

Measurements of density, Young's modulus, and loss factor have been made on a number of samples of PVC and MDPE (typical plastics used for water pipes), and representative values have been determined.

# 6 *Wavenumber measurements*

## 6.1 *Introduction*

In order to validate the theoretical model described in [3], wavenumber measurements of the axisymmetric 'fluid-borne' wave in a fluid-filled, buried pipe need to be made. In this section a method is described for measuring the wavenumber using three equispaced transducers. In the preliminary experiment which follows measurements are made on a water-filled MDPE pipe in vacuo. the results are then compared with theoretical predictions for the in vacuo case. This measurement procedure will then form the basis for future measurements on a buried pipe.

## 6.2 *Theoretical basis for wavenumber measurement*

Consider a fluid-filled pipe of arbitrary length, as shown in figure 6.1. A plane pressure excitation $p_0 e^{i\omega t}$ is applied at the end $x$=0.

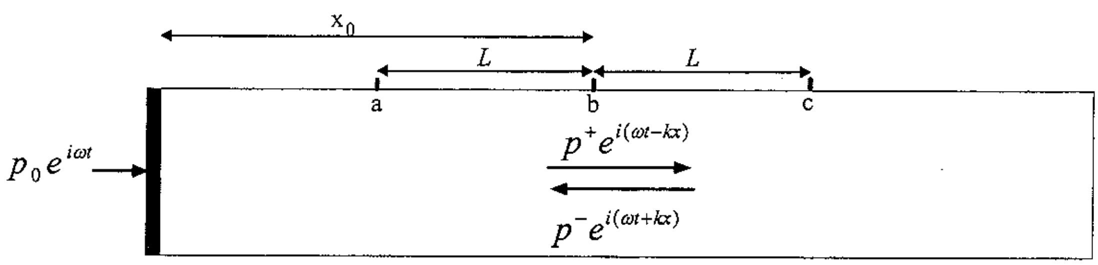



Figure 6.1

One-dimensional waves in fluid-filled pipe

The sum of all the monochromatic plane waves travelling in the positive x-direction can be represented by

$$p(x,t) = p^+e^{i(\omega t-kx)} \tag{6.1}$$

and those travelling in the negative x-direction by

$$p(x,t) = p^-e^{i(\omega t+kx)} \tag{6.2}$$

Hence the total acoustic pressure along the pipe is given by

$$p(x,t) = p^+e^{i(\omega t-kx)} + p^-e^{i(\omega t+kx)} \tag{6.3}$$

Consider three equispaced locations along the pipe at points *a, b,* and *c*, at $x=x_0-L$, $x=x_0$, and $x=x_0+L$ respectively, as shown in figure 6.1.

Ignoring the time dependence,

$$p(a) = p^+ e^{-ik(x_0 - L)} + p^- e^{ik(x_0 - L)} \tag{6.4}$$

$$p(b) = p^+ e^{-ikx_0} + p^- e^{ikx_0} \tag{6.5}$$

$$p(c) = p^+ e^{-ik(x_0 + L)} + p^- e^{ik(x_0 + L)} \tag{6.6}$$

From equations (6.4), (6.5) and (6.6), $p+$ can be expressed in terms of $p(a)$ and $p(b)$, or in terms of $p(b)$ and $p(c)$

$$p^+ = \frac{p(a) - p(b)e^{-ikL}}{2i \sin kLe^{-ikx_0}} \tag{6.7}$$

$$p^+ = \frac{p(b)e^{ikL} - p(c)}{2i \sin kLe^{-ikx_0}} \tag{6.8}$$

Equating the above two expressions gives an expression for the wavenumber $k$ in terms of the pressures $p(a)$, $p(b)$, and $p(c)$.

Provided that $kL \neq n\pi$,

$$\cos kL = \frac{p(a) + p(c)}{2p(b)} \tag{6.9}$$

or

$$k = \frac{1}{L} \arccos\left( \frac{p(a) + p(c)}{2p(b)} \right) \tag{6.10}$$

## 6.3 *Experimental set-up & procedure*

The experimental arrangement is shown in figures 6.2 & 6.3. It consisted of a water-filled MDPE pipe, approximately 2m in length, secured vertically, with the lower end sealed. The water column was excited at the upper end by an electrodynamic shaker attached to a light, rigid piston. The external diameter of the pipe was 180mm, with the wall thickness being 11mm. The centre section of the pipe was instrumented with four PVDF wire transducers, three of which were spaced 0.5m apart, with the fourth mid-way between the upper two of the three, as shown in figure 6.3. The piston was excited with a swept sine input from 10Hz to 1kHz, and the signals from the PVDF wire transducers were acquired into an HP analyser.

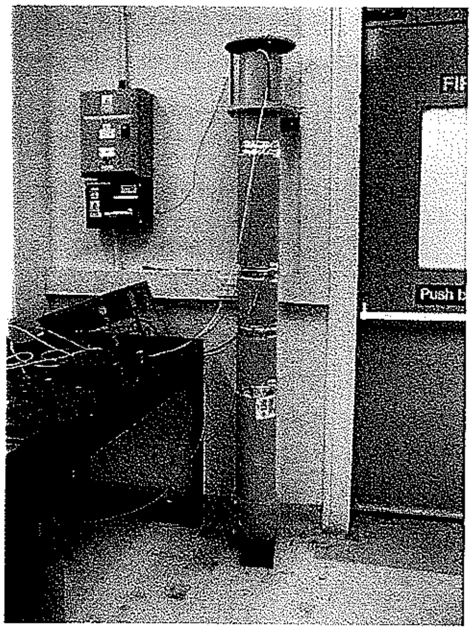


Figure 6.2
MDPE pipe

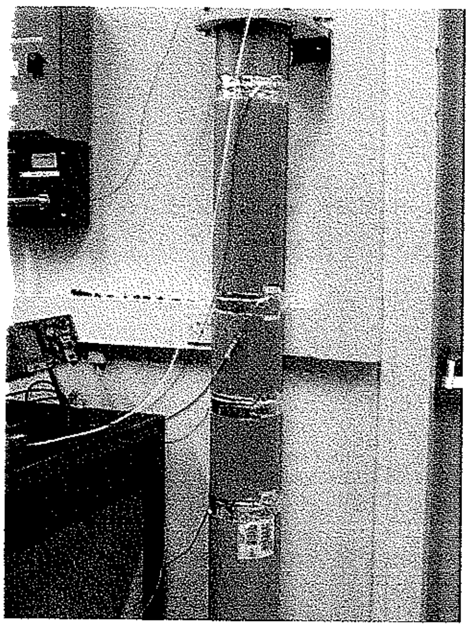


Figure 6.3
Four ring transducers on MDPE pipe

## *6.4 Data analysis*

The transducer arrangement described above allows for two sets of three equispaced pressure measurements to be analysed, one set with a 0.25m spacing, and the second set at 0.5m spacing.

The wavenumber was calculated using equation (10) from each of the two sets of three transducer measurements. The real and the imaginary components are shown in figure 6.4, along with the theoretically predicted value. Figure 6.4a shows good agreement between the measured and predicted values for the real part of the wavenumber, particularly at low frequencies. The deterioration of agreement with increasing frequency is as expected given that the theoretical predictions are only valid well below the ring frequency (~2kHz for the MDPE pipe). The data for the more closely spaced set is slightly noisier than for the widely spaced transducers, the differences being greater at low frequencies. Again, this is as expected, given that discrimination for the longer wavelengths will be improved with more widely spaced transducers, particularly near pressure antinodes. Figure 6.4b shows that the agreement between the measured and predicted data for the imaginary part of the wavenumber is less good than for the real part. The mean values for the measured data show good agreement, particularly at low frequencies, but the deviations from the mean are larger. Again, the data from the more widely spaced transducers are superior.

However, one disadvantage to the more widely spaced transducers is associated with "unwrapping" of the data. Once there is more than half a wavelength between adjacent transducers, the data must be "unwrapped" when the arccos of the pressure ratios is calculated (equations (6.9) and (6.10)).

$$\mathrm{Re}\{k_{unwrap}\} = \frac{1}{L}(2n\pi - \mathrm{Re}\{k_{pv}\})\, n \text{ odd} \tag{6.11}$$

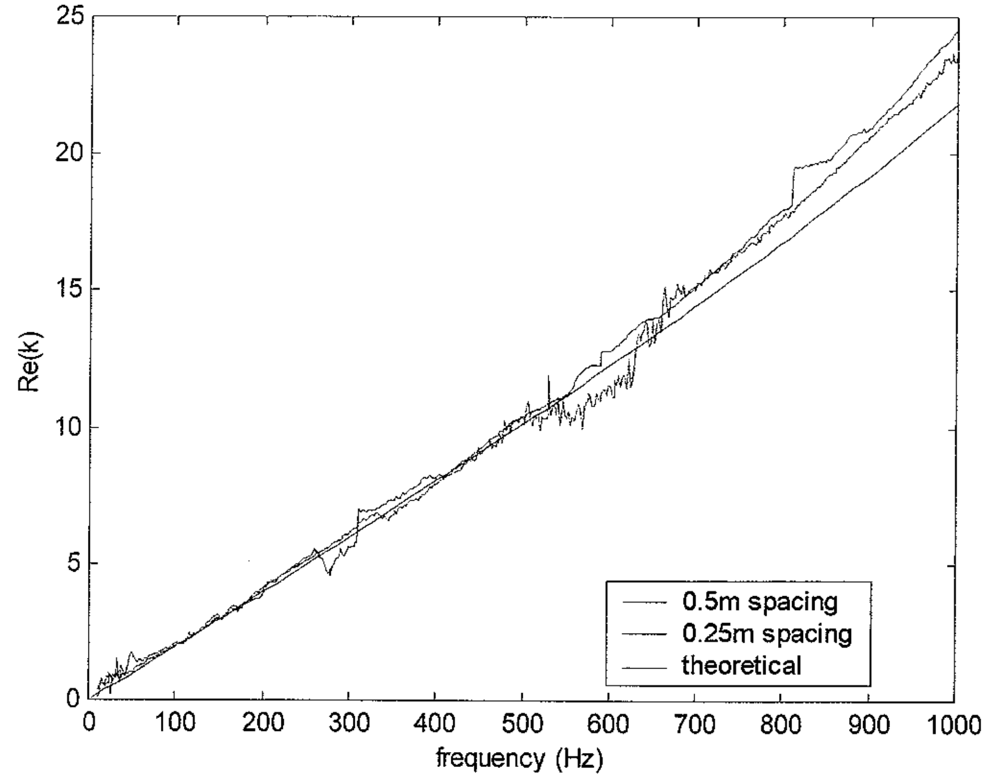
$$\mathrm{Re}\{k_{unwrap}\} = \frac{1}{L}(n\pi + \mathrm{Re}\{k_{pv}\})\ n \text{ even} \tag{6.12}$$

$$\mathrm{Im}\{k_{unwrap}\} = \frac{1}{L}(-1)^n\, \mathrm{Im}\{k_{pv}\} \tag{6.13}$$

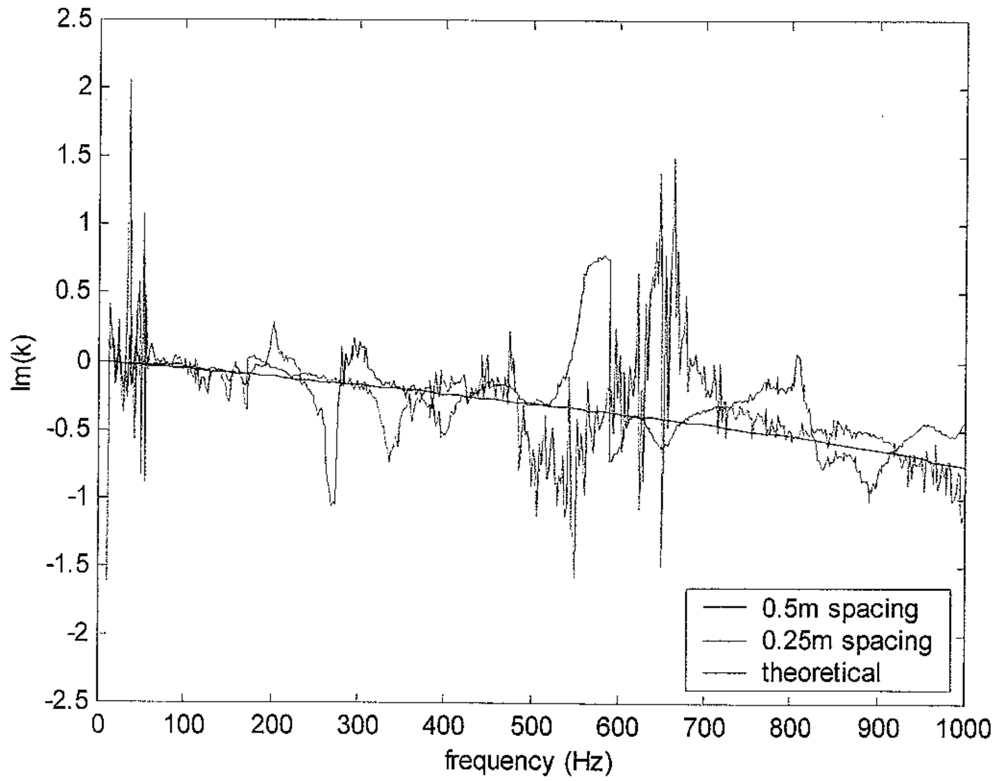
where $k_{pv}$ is the wavenumber calculated from the principle value of the arccos, and $n$ is the number of half wavelengths between adjacent transducers

Figure 6.5 shows measured values of $\mathrm{Re}\{\cos kL\}$ plotted against frequency for both sets of data. Figure 6.6 shows the pre- and post-unwrapped data for the real part of the wavenumber for the 0.5m spaced transducers.

Clearly, the further apart the transducers are spaced, the more "unwrapping" will need to be done, and a balance must be achieved between the improved discrimination achieved with widely spaced transducers, and the number of half wavelengths occurring between them at the maximum frequency of interest.




(a)




(b)

Figure 6.4
(a) Real & (b) imaginary components of wavenumber for the axisymmetric 'fluid-borne' wave

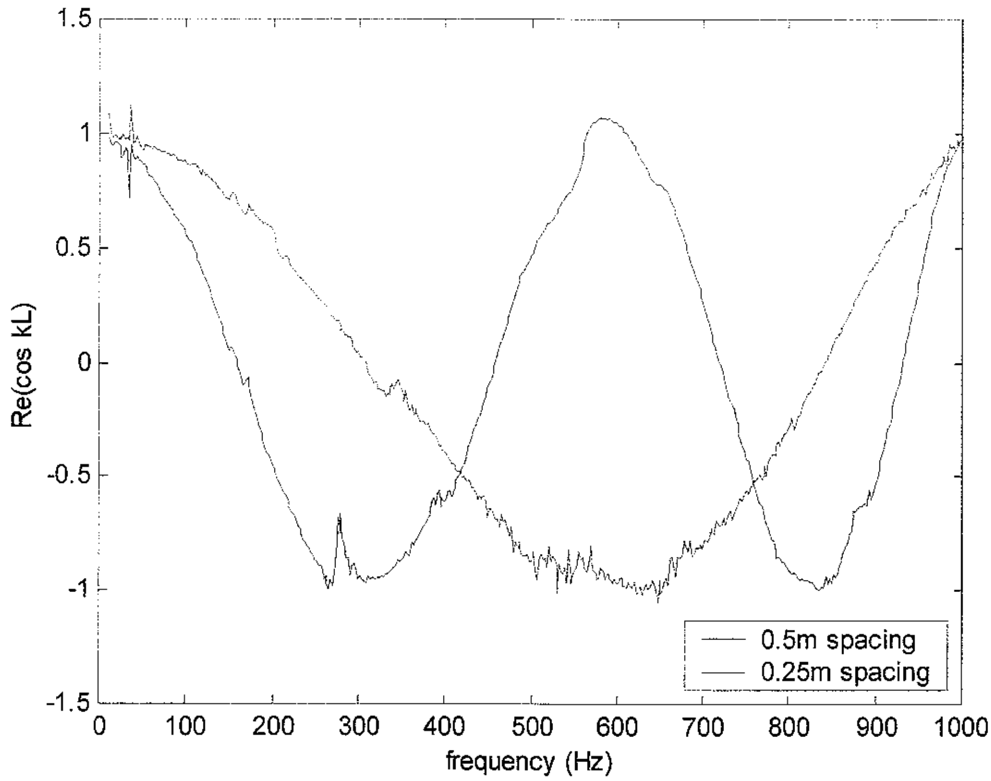



Figure 6.5
Re{cos*kL*} vs frequency

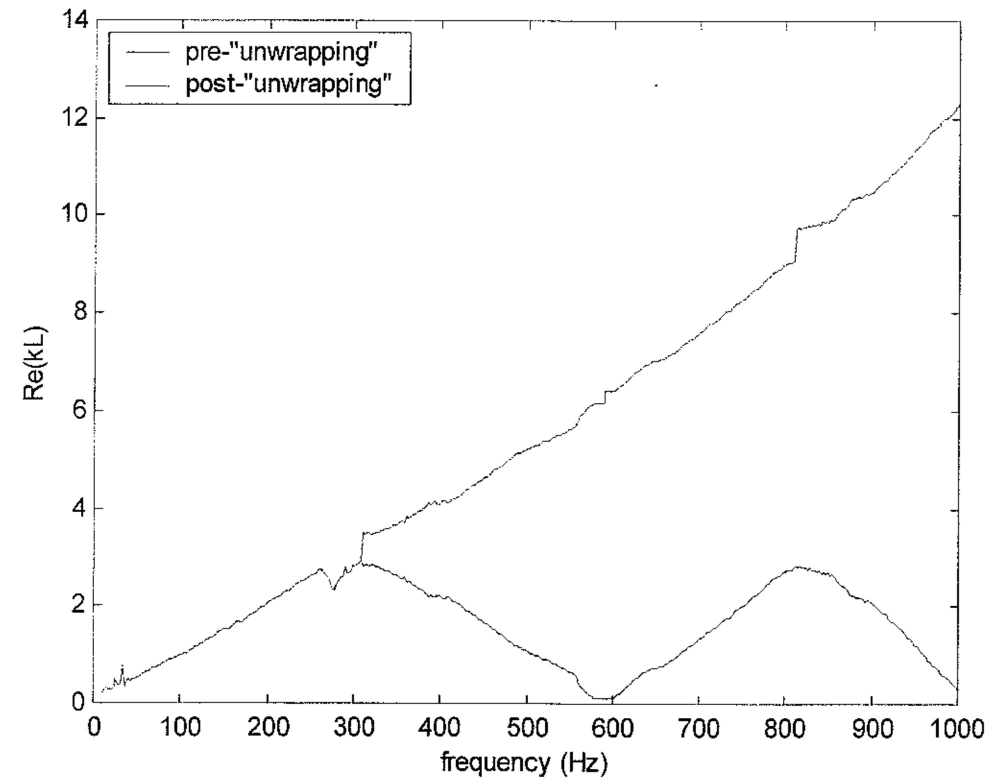



Figure 6.6
Re{*kL*} vs frequency pre- and post-"unwrapping"

## *6.5 Summary*

A method has been described for measuring the wavenumber of the axisymmetric 'fluid-borne' wave in a pipe, using three equispaced transducers. Measurements have been made on a water-filled MDPE pipe in vacuo. These measurements show good agreement with the theoretical predictions in terms of both wavespeed and attenuation.

# 7 *Buried pipe facility at the University of East Anglia, Norwich*

## 7.1 *Introduction*

During the early stages of this project, contact was made with a research team at the University of East Anglia, Norwich, (UEA), who were in the process of building and commissioning a buried pipe facility on the UEA campus. The UEA team were keen to collaborate and it was agreed that we would instrument the pipe with a number of PVDF ring transducers and make some wavenumber measurements in due course.

## 7.2 *The UEA facility*

The UEA pipe facility consists of a 24m length of 180mm diameter MDPE pipe buried in the ground at a depth of approximately 1.2m. The pipe is terminated at each end by a large water tank, filled with water to ground level, and is unpressurised except by the head of water in the tanks. The pipe is constructed from six 4m sections, with three T-sections giving access to the surface. One of the T-sections is fitted with a standard fire hydrant, the other two with gate valves allowing clear access to the inside of the main pipe.

Each of the 4-metre sections has two hydrophones mounted in the wall of the pipe in such a way that the active surface of the hydrophone is flush with the inside bore of the pipe. The hydrophones are positioned 1m from the end of each section. The hydrant T-section also has two hydrophones fitted, one on the horizontal bore and one on the riser. Four geophones were also attached to the pipe.

The signals from the sensors are digitised in pairs, and returned to an equipment hut via a digital link.

In addition, the ISVR team instrumented the pipe with two sets of three equispaced ring transducers (one set using Vibetek 20 wire, and one set using Vibetek OT017 wire), set at 1.1m apart, on one of the centre sections of the pipe.

## 7.3 *Measurements*

Preliminary measurements made on the UEA rig have revealed some problems with the acquisition system and possibly the signal conditioning. These problems are in the process of being rectified, but unfortunately, to date, no reliable measurements are available for analysis. Further measurements are planned for the forthcoming follow-on project.

# 8. *Conclusions*

In this report, a number of experiments have been described.

Two types of PVDF wire have been calibrated as ring transducers for measurement of the pressure inside an elastic, fluid-filled pipe; furthermore the wire ring transducers have been integrated with existing leak noise correlation equipment, and a simulated leak has been detected. In addition, preliminary tests have been undertaken on two novel, part-ring transducers.

Measurements of Young's modulus and loss factor have been made on a number plastic samples, typically used in the water industry, as a pre-requisite for predicting wave behaviour in plastic water pipes. A procedure for making wavenumber measurements of the 'fluid-borne' axisymmetric wave in a pipe has been developed, and measurements have been made on an MDPE pipe in the laboratory. These measurements have been compared with theoretical predictions, and good agreement was shown.

Finally, a brief description of a buried pipe facility at UEA, Norwich, is included, on which measurements will be made in the near future.

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